# High upper critical field and irreversibility field in $MgB_2$ coated-conductor fibers

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We report on structural and superconducting properties of round $MgB_2$ coated-conductor fibers deposited by hybrid physical-chemical vapor deposition on SiC fibers. The coating is polycrystalline and composed of elongated crystallites with dimensions less than 1 $\mu$m in length and 0.2 $\mu$m in width. The pure $MgB_2$ fiber shows a zero-resistance $T_c$ of 39.3 K. The carbon-alloyed fibers show a high upper critical field of 55 T at 1.5 K and a high irreversibility field of 40 T at 1.5 K. The result demonstrates great potential of $MgB_2$ coated conductors for superconducting magnets. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2149289]

The recently discovered superconductor $MgB_2$ (see Ref. 1) is a promising material for high-magnetic-field applications.[2] The transition temperature at 40 K allows practical operation above 20 K using cryocoolers. Unlike high temperature superconductors where critical current density $J_c$ drops sharply across the grain boundary when the grains are misaligned, grain boundaries do not degrade $J_c$ in $MgB_2$.[3,4] Wires and tapes of $MgB_2$ have been made using the so-called "powder-in-tube" (PIT) technique with encouraging results.[5–7] $MgB_2$ conductors also promise lower cost.[3] Recently, we have shown record high values of upper critical field $H_{c2}(0)$ over 60 T in textured carbon-alloyed $MgB_2$ thin films produced by hybrid physical-chemical vapor deposition (HPCVD).[8] Whether such record high values can be achieved in forms more suitable for practical conductors is of great interest. Here we report on polycrystalline carbon-alloyed $MgB_2$ coated-conductor fibers with high $H_{c2}$ (the field at which a superconductor becomes normal) and high irreversibility field $H_{irr}$ (the field at which a superconductor ceases to carry supercurrent). The result demonstrates great potential of the coated conductor approach towards $MgB_2$ high-field wires for superconducting magnets.

Coated conductors have been widely studied for high temperature superconductors.[3,4] Coated conductors have also been explored for $MgB_2$ by sputtering on Hastelloy[9] and by electroplating on stainless steel.[10] These works have generated $H_{c2}$ and $H_{irr}$ values similar to those of PIT $MgB_2$ wires. In this work, the $MgB_2$ coated conductors were grown by HPCVD[11] on round SiC fibers with a tungsten core.[12,13] Details of the HPCVD process have been described elsewhere.[11] The SiC/W fibers, about 1 cm in length, were placed on the top horizontal surface of the susceptor (heater) and heated to 685–720 °C in $H_2$ carrier gas during the deposition. Heated Mg chips placed near the SiC fibers served as the Mg source while $B_2H_6$ was the B source. The deposition rate was about 0.1 $\mu$m/min at 700 °C. Some fibers were coated multiple times to achieve thicker coating. For the deposition of the carbon-alloyed $MgB_2$ coating, we added bis(methylcyclopentadienyl)magnesium $[(MeCp)_2Mg]$, a carbon-containing metalorganic magnesium precursor, to the gas flow during the deposition, and the carbon content in the coating was controlled by the flow rate of a secondary hydrogen flow passing through the $(MeCp)_2Mg$ bubbler.[14]

Figure 1 shows scanning electron microscope (SEM) images of a round $MgB_2$ coated-conductor fiber. The diameter of the SiC fiber is ~100 $\mu$m with a tungsten core of ~10 $\mu$m.[13] Except for a defect spot, Fig. 1(a) shows a uniform coating of the fiber. Figure 1(b) shows that the SiC fiber has a columnar structure along the radial direction.[12] The $MgB_2$ coating, seen as the bright layer on the surface of the fiber, is about 0.75 $\mu$m in thickness. Although the fiber was coated only once, it shows a relatively uniform thickness of the $MgB_2$ layer without shadow effect, which is due to the high gas pressure (100 Torr) and the diffusive nature of the deposition process. Figure 1(c) is a blown-up view that shows more clearly the microstructure of the coating. The $MgB_2$ coating has a granular structure with randomly oriented crystallites. The grains are elongated with length less than 1 $\mu$m and width of 0.2 $\mu$m. This microstructure is very similar to those in some early polycrystalline $MgB_2$ films.[15]

The structure of the $MgB_2$ coating was further studied by x-ray diffraction using a two-dimensional area detector. The integrated area diffraction $\theta-2\theta$ scan is shown in Fig. 2. The peaks from the SiC fiber, marked by "*," indicate that SiC is

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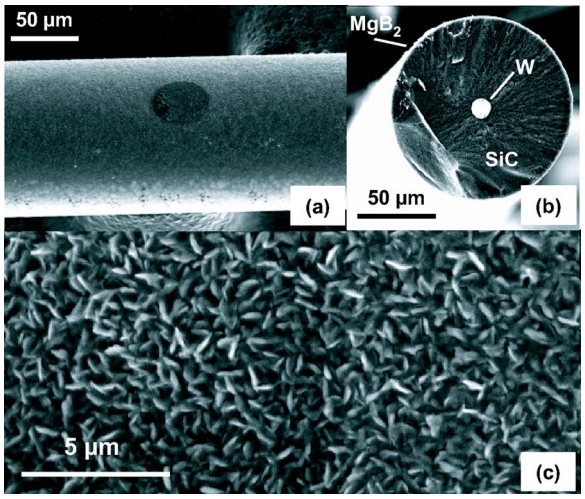


FIG. 1. (a) Scanning electron microscope (SEM) images of a $MgB_2$ coated-conductor fiber. (b) A cross-section image of the $MgB_2$ coated-conductor fiber. (c) A blown-up SEM image of the surface, showing elongated $MgB_2$ crystallites with random orientations.

of the 3C polytype ($\beta$-SiC, zinc blende structure).[16] Several diffraction peaks off different $MgB_2$ planes are seen, indicating that the $MgB_2$ crystallites are oriented randomly. The polycrystalline nature of the microstructure and the small grain size make the diffraction intensity from $MgB_2$ weak. The lattice constants of the $MgB_2$ layer are $a=3.078\pm0.01$ Å and $c=3.514\pm0.005$ Å, matching very well with the bulk values of pure $MgB_2$.[1] Also observed are diffraction peaks due to $Mg_2Si$. It could be the result of reaction of Mg with SiC[17] or with the free Si existing in the SiC fiber.[13]

The superconducting properties of the coated-conductor fibers are similar to those in epitaxial pure $MgB_2$ and textured carbon-alloyed $MgB_2$ films deposited by HPCVD. For example, a pure $MgB_2$ fiber shows a zero-resistance transition temperature $T_c$ of 39.3 K. It has a residual resistivity of $\rho_0 \sim 30\ \mu\Omega$ cm, much higher than that in the clean epitaxial HPCVD $MgB_2$ films ($\rho_0 \sim 0.28\ \mu\Omega$ cm[18]), and a residual resistance ratio of $RRR=R(300\text{ K})/R(50\text{ K})=2.54$, much smaller than that in the clean films ($RRR \sim 30$[18]). This is due to the granular nature of the layer and the existence of semiconducting $Mg_2Si$, presumably at the grain boundaries.

Measurements in magnetic field were carried out at the National High Magnetic Field Laboratory at Florida State University (dc field, up to 30 T) and Los Alamos National Laboratory (pulsed field, up to 60 T). Figure 3 shows voltage versus applied magnetic field curves measured at different temperatures for three $MgB_2$ coated-conductor fibers: (a) a pure clean $MgB_2$ fiber, (b) carbon-alloyed $MgB_2$ fiber 1, and (c) carbon-alloyed $MgB_2$ fiber 2. The measurement currents are 100, 50, and 50 $\mu$A for the three fibers, respectively. Carbon alloying suppresses $T_c$ and increases resistivity of the coating, leading to larger voltage signals in the carbon-alloyed $MgB_2$ fibers than in the pure $MgB_2$ fiber. From these curves, $H_{c2}$ and $H_{irr}$ are determined by the following criteria: $R(H_{c2})=0.9R_0$ and $R(H_{c2})=0.1R_0$, where $R_0$ is the residual resistance above the superconducting transition.

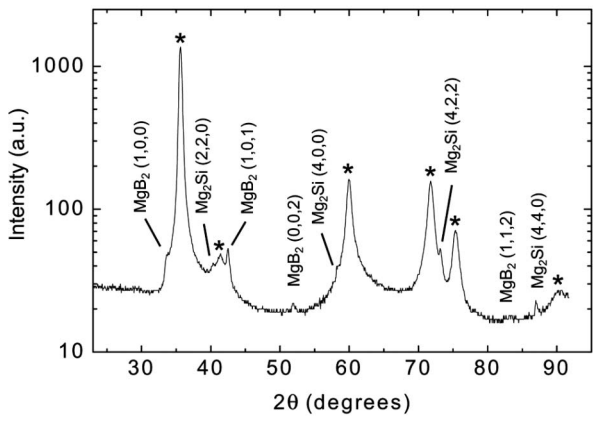


FIG. 2. Integrated x-ray diffraction $\theta-2\theta$ scan of a pure $MgB_2$ coated-conductor fiber collected using a two-dimensional area detector.

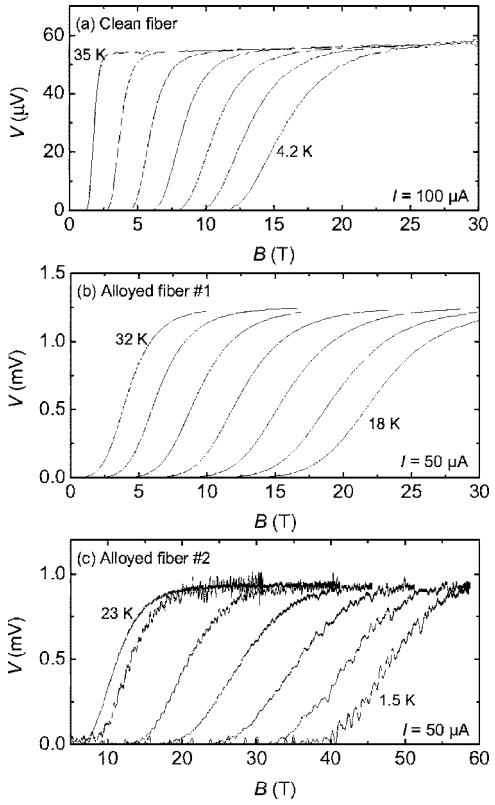


FIG. 3. Voltage-magnetic field curves for (a) a pure $MgB_2$ fiber, (b) carbon-alloyed $MgB_2$ fibers 1, and (c) carbon-alloyed $MgB_2$ fibers 2. For each set of data, the lowest and the highest temperatures of the measurements are shown.

Previously, we have shown textured films of carbon-alloyed $MgB_2$ prepared by HPCVD $H_{c2}$ of 51 T in parallel field and 35 T in perpendicular field at 4.2 K.[8] Since the $MgB_2$ grains in the coated-conductor layers are randomly oriented, $MgB_2$ grains with $a-b$ grains parallel to the applied field become normal at a higher field than those whose $a-b$ grains are perpendicular to the applied field, with grains of other orientations in between. Because $H_{c2}$ measures the onset of superconductivity, the measured $H_{c2}$ values in the coated-conductor fibers should be similar to the higher, parallel-field $H_{c2}$ in the textured films. On the other hand, as soon as the superconducting $MgB_2$ grains form a continuous path, the fiber will reach zero resistance, which is measured by the $H_{irr}$ values in the coated-conductor fibers.

Figure 4 shows the temperature dependencies of (a) $H_{c2}$ and (b) $H_{irr}$ for the three fibers in Fig. 3. The clean fiber has an $H_{c2}(4.2\text{ K})$ of 20 T, which is dramatically enhanced by carbon alloying. At $T=1.5$ K, alloyed fiber 2 shows an $H_{c2}$ of

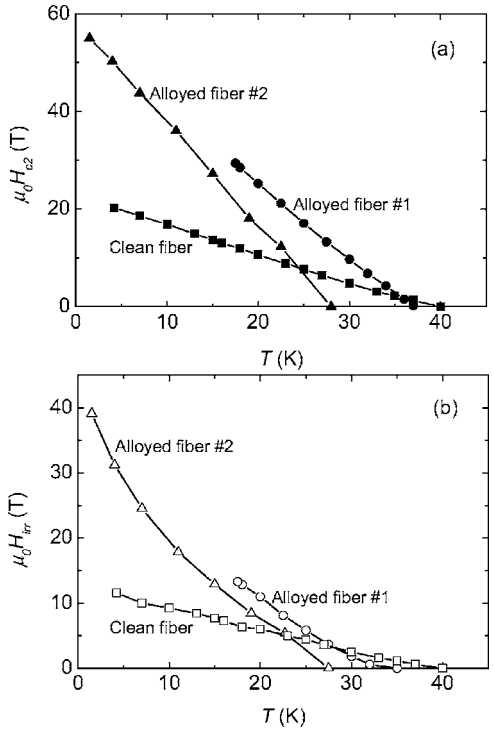


FIG. 4. Temperature dependencies of (a) $H_{c2}$ and (b) $H_{\mathrm{irr}}$ for the three $MgB_2$ coated-conductor fibers shown in Fig. 3.

55 T, and at $T=25$ K, alloyed fiber 1 has an $H_{c2}$ of 17 T. The enhancement of $H_{c2}$ by carbon alloying can be qualitatively explained by the modifications of intraband and interband scattering in the two ($\sigma$ and $\pi$) bands of $MgB_2$.[19] Similar dramatic enhancement by carbon alloying is also seen in $H_{\mathrm{irr}}$, indicating an increase in the flux pinning by carbon alloying. An $H_{\mathrm{irr}}$ value of 40 T at $T=1.5$ K is obtained in alloyed fiber 2, while $H_{\mathrm{irr}}$ is 5.8 T at $T=25$ K for alloyed fiber 1. The $H_{c2}$ and $H_{\mathrm{irr}}$ reported here are substantially higher than those previously reported for PIT $MgB_2$ wires ($H_{c2}\sim 37$ T in carbon-doped $MgB_2$ PIT wires[20] and $H_{\mathrm{irr}}\sim 25.4$ T at 4.2 K in $MgB_2$ PIT wires with addition of SiC nanoparticles[21]). The differences may be due to the different microstructures: in carbon-doped bulk $MgB_2$, the *a* axis shrinks but *c* axis remains constant with increasing carbon concentrations,[22] whereas in HPCVD films both *a* and *c* axes expand with carbon alloying.[14]

The result here demonstrates that epitaxy and texture are not necessary for achieving high $H_{c2}$ and $H_{\mathrm{irr}}$. This is important for practical manufacturing of $MgB_2$ conductor wires. The high $H_{c2}$ and $H_{\mathrm{irr}}$ are very attractive for superconducting magnets in magnetic resonance imaging (MRI) systems.[23] In particular, the operating temperature above 20 K allows replacement of liquid helium by efficient cryocoolers, so that MRI systems could become lighter, of lower operation cost, more reliable, and more accessible to populations in remote locations or in developing countries.[24,25] The HPCVD technique used here is adaptable to scale up for continuous and uniform coating of long length fibers. High $MgB_2$ deposition rate, which is important for manufacturing, has been demonstrated up to 1.2 $\mu$m/min by HPCVD.[26] Although the large diameter SiC fiber used in this work is not the desirable substrate for practical conductor wires because it is brittle and costly, $MgB_2$ coatings can be made on inexpensive and strong metallic wires such as stainless steel.[10,26] Therefore, the $MgB_2$ coated conductor fabricated using HPCVD could be seriously considered as a potential alternative to the current Nb-based high-field conductors.

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